Correcting Tidal Responses in Observed Water Well Levels During Coastal Aquifer Tests

CORRECTING TIDAL RESPONSES IN OBSERVED WATER WELL LEVELS DURING COASTAL AQUIFER TESTS

by

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ABSTRACT

A modified tidal efficiency algorithm, ESTA, was developed to correct observed water well levels in tidally responsive coastal areas to get best estimates of aquifer properties and well production characteristics. The algorithm was developed during groundwater studies in Puerto Peñasco, northeastern Gulf of California, Sonora, Mexico. ESTA predicts standing water well levels in response to tides. ESTA requires initial sea and well calibration data, from which sea-well relationships are calculated. It needs tidal data for the time period when projected standing water well levels are desired. The method uses a single cosine or sine function for rising or falling tides, respectively. ESTA tended to overpredict water levels, especially on rising tides, on the average of about 0.05 ft, as shown in analyses at five coastal well sites completed in low to moderately permeable sand and coquina. ESTA can be improved by application of error analysis, but this will not be necessary in most cases, as errors are generally very small for most aquifers and tidal ranges. When ESTA was applied to an aquifer test in highly permeable coral near Kahuku, northshore Oahu, Hawaii, rising-tide water well levels were overpredicted and falling-tide water well levels were underpredicted by 0.10 and 0.33 ft, respectively. Error analysis reduced these errors to 0.06 and 0.16 ft.

INTRODUCTION

Hydrogeologists know that tides influence groundwater levels in coastal aquifers. In fact, tidal responses in wells may be used to roughly estimate aquifer storativity and transmissivity, if one assumes, or independently determines, one value to reckon the other (Jacob, 1940, 1950; Ferris, 1951; Werner and Norén, 1951; Todd, 1960; Carr and VanderKamp, 1969).

During aquifer and well production tests in tidally responsive coastal aquifers, observed water levels must be corrected to get best estimates of aquifer properties and production characteristics (Walton, 1962, p. 3-4). Corrections are needed to remove tidal impacts, and produce drawdown values which represent only aquifer responses to pumping wells.

Rough corrections may be made by applying simple tidal efficiency equations (Walton, 1962, p. 4). Better corrections can be made using mathematical and electric analog models developed by Williams and others (1970) and Williams and Liu (1971). This is a time-consuming and costly inverse analysis, where extensive historic water level data are needed, and aquifer properties must essentially be assumed beforehand.

Groundwater studies in Puerto Peñasco were conducted from 1978 to 1980 to develop a seawater supply for commercial controlled-environment shrimp aquaculture (Water-Supply Study Team, 1979; Popkin, 1979, 1980a; DeCook and others, 1980). These studies included pumping tests on five sets of dual test wells (Popkin 1979, 1980a) with observation wells. Earlier hydrogeologic studies (Crowe, 1968-1978; Riley and Percious, 1974; Percious, 1976) were conducted in a smaller area without benefit of observation wells.

The University of Arizona's Environmental Research Laboratory (ERLAB), with Universidad de Sonora, has operated a research station since 1962 (U.E.P., Unidad Experimental Peñasco) at Puerto Peñasco, northeastern Gulf of California, (Sea of Cortez) Sonora, Mexico, and a commercial shrimp prototype farm from June 1978 to June 1980. Research projects have included solar distillation of

seawater, greenhouse vegetable agriculture, controlled-environment shrimp aquaculture, and halophyte irrigation. These require a dependable supply of filtered temperate seawater.

Tides in the northern Gulf of California are of the irregular semidiurnal type: there are usually two high and two low tides each day, each of a different height. In Puerto Peñasco, August tidal ranges may approach 26 ft.

The test wells, within 1,000 ft of the sea, were in a tidally responsive coastal aquifer. It was necessary to correct observed water well levels for aquifer analysis and well production tests. Tidal efficiency equations were found to be too inexact, while modeling was impossible because of lack of historic data and accurate hydraulic estimates. A modified tidal efficiency algorithm, ESTA, was developed, evaluated, and applied to the problem. ESTA: "that's it."

This report presents the ESTA algorithm, summarizes its properties, and suggests how it can be used and improved. ESTA is also applied to a Hawaiian aquifer test, where tidal ranges were relatively small and permeability was very high compared to the Peñasco case.

AQUIFER TESTS AND TIDAL CORRECTIONS

Five dual seawater well sites (Plate 1) were drilled and tested: Site 1 near Estero Marua Shipwreck, and four coastal sites from ERL Well #5 to Las Conchas Park along Las Conchas Road. (The Estero rarely receives streamflow but, like the coastal sites, responds to tides.) Site 1 was developed in alluvial sand, while the coastal sites were developed in coquina.

Data were collected and analyzed on drill cuttings, well discharge, pumping and static water well levels, pumping and tidal response levels, sea and estero levels, and discharge water quality (Popkin, 1979). Pumping tests were conducted, with at least three days of pumping at each site, and water levels were measured in the pumping well and nearby observation well.

Since fluctuations in sea level due to tides influence standing groundwater levels, it is not simple to estimate drawdown. Correlation of water well levels and time observations with tidal data offers an approach to correct drawdown estimates to account for tidal impacts.

The equation for the tides of Puerto Peñasco used to generate tidal charts and calendars includes 37 harmonic constituent cosine pairs (Matthews, 1968). Even so, it appears that tidal predictions are only accurate to within 0.5 ft and 20 minutes of observation. This may be because more harmonic terms need description, and there are variations in winds which preclude harmonic tidal analysis.

Appendix A-1 presents the ESTA algorithm to predict standing water level data from tidal data. The method utilizes _Tablas de Predicción de Mareas_ (Universidad Nacional Autónoma de Mexico, 1979), and a single cosine or sine function for rising or falling tides, respectively. Appendix A-2 shows the ESTA calibration values developed for the algorithm for a representative test site.

The algorithm tends to overpredict water levels, especially on rising tides, on the average of about 0.05 ft (0.03 ft for production test wells along Las Conchas Road). This seems acceptable, as tidal chart data are reported to 0.1 ft, and water levels are measured either to 0.01 ft in observation or 0.01 m (0.03 ft) in pumping wells. Also, average range in water level response for the dual well sites was observed as 0.47 ft (0.29 ft for the Las Conchas Road wells). The percent error for this method, based on the ratio of the average error to the average range in standing water level, is 10.6 percent (10.3 percent for the Las Conchas Road wells). Appendix A-3 summarizes the error analysis.

TIDAL ANALYSIS

Tidal responses of standing water well levels can be used to roughly estimate aquifer properties. The analysis assumes that sea level varies with a simple harmonic motion, and propagates a train of sinusoidal waves inland from the aquifer's submarine outcrop.

Transmissivity is estimated by:

$$T = 0.6\ P\ S\ (D\ /\ L)^2 \qquad \text{(Todd, 1960, p. 164)}$$

where

T = transmissivity (gpd/ft)
P = tidal period (days)
S = storativity
D = distance from well to mean sea (ft)
L = tidal lag time (days)

Appendix B-1 summarizes tidal derived estimates of aquifer transmissivities, and shows distances of test sites to the sea. Wells along Las Conchas Road averaged about 800 ft inland, with an average tidal efficiency of 1.8 percent.

Appendix B-2 summarizes transmissivity estimates based on recharge boundary and tidal analysis. These are probably closer to the true values than B-1. These estimates are averages which extend over the large distance between test wells and the Gulf. They tend to be overestimates near a well, but fair estimates for a producing field.

At Peñasco, both tidal fluctuation and well response are not simple harmonic waves. Well responses show truncated high-tide response peaks, and flattened low-tide response troughs. These appear similar to streamflow hydrographs responding to a storm, showing a rapid rise followed by longer delayed drainage. This type of response produces longer lag times for low tides than high tides, and consequently lower transmissivity estimates for low-tide than high-tide data. Low-tide lag times were from 1.17 to 2.38 times high-tide lag times in wells completed along Las Conchas Road.

AVERAGE AQUIFER PROPERTIES

Aquifer test data, interpreted according to tidal, specific capacity, recovery, Theim, Theis and Cooper-Jacob analyses (Walton, 1962) indicate a range of values for aquifer properties. Short pumping period, dynamic tidal impacts, inefficient well design, poor development, and inadequate pump submergence contribute to this range. They account for underestimates using specific capacity and Theim methods, and for overestimates using recovery methods. Areal changes, boundary dynamics, and storativity uncertainties account for overestimated values derived from tidal analyses.

The best estimate of aquifer properties appears from the non-steady methods of Theis and Cooper-Jacob. From these analyses and other hydrogeologic inferences, average aquifer properties along Las Conchas Road are summarized in Table 1.

TABLE 1. SUMMARY OF AQUIFER PROPERTIES ALONG LAS CONCHAS ROAD

Transmissivity: 200,000 gpd/ft, or 26,700 ft^2/day
Hydraulic conductivity: 4,450 gpd/ft^2, or 600 ft/day
Storativity: 0.05 to 0.5
Saturated aquifer thickness: 45 ft, or 13.7 m
Coquina thickness: 24 ft, or 7.3 m

Water levels in the coquina aquifer along Las Conchas Road are controlled by recharge from the nearby Gulf of California. The effective recharge zone is closer to high-tide water than mean-tide water. This was found from well-image boundary analysis.

Most hydrogeologists acknowledge that the best field estimates of transmissivity are within 20 percent of the real aquifer value, if the correct aquifer model is known, and within 50 percent if not (Walton, 1980). Best estimates of storativity are within a log cycle or order of magnitude for the confined aquifers, and within 50 percent for unconfined aquifers. Transmissivity and conductivity estimates in Table 1 are probably within 20 to 40 percent accurate. Storativity estimates cover the likely range.

A misleading risk is achieved by believing that many tests or analyses which produce similar aquifer property estimates will somehow "average out" to closely describe the real properties of the aquifer. Such information only shows that the analysis method converges on average values. It says nothing about how close these average values approximate the aquifer's real values. Standard statistical analysis is insufficient because it cannot account for important errors in aquifer, well, and pump idealization. In other words, precision must not infer validity.

ALGORITHM USE AND IMPROVEMENTS

The ESTA algorithm requires initial sea and well calibration data, from which sea-well relationships are calculated. It needs tidal data for the time period when projected standing water well

levels are desired. If these are not available or extractable, a temporary sea staff gage or coastal stilling well can be established. Appendix A-1 defines all ESTA variables, and shows appropriate relations and calculations.

The algorithm may be improved by application of error analysis. After ESTA is applied to generate the "new water well level" (NWL), one correction for a falling tide and another correction for a rising tide can be calculated for each well site, based on error analysis. In most cases these improvements will not be necessary, as errors will generally be very small except in highly permeable aquifers, in high tidal ranges, where wells are very close to the sea, and/or where tidal efficiencies are high.

The ESTA algorithm and error-analysis improvements may be computerized on a programmable pocket calculator, or more sophisticated computer.

HAWAIIAN APPLICATION

In August 1980, ESTA was applied to an aquifer test on a seawater well developed in the highly permeable coral near Kahuku, northshore Oahu, Hawaii (Popkin, 1980b). Though local tidal variations are relatively small (maximum range about 2.6 ft), the high hydraulic conductivity of the coral makes tidal impacts significant in analyzing well responses to pumping.

According to Gerritsen (1978, p. 19):

> Tides in the Hawaiian Archipelago are of the mixed semidurnal type. (There is...) a significant daily inequality in which there is a considerable difference in the elevation of successive high waters during spring tide and strong diurnal characteristics during neap tides.

Tidal projections from Laie Bay (National Ocean Survey, 1979; Evergreen Pacific, 1980), about 4 miles southeast of the well site, showed a tidal range of 2.2 ft. These projections are based on many years of observations. The well, which was 600 ft inland from the Pacific Ocean, indicated a water well level range of 2.13 ft. This is a tidal efficiency of about 97 percent. Since the corrected specific capacity of the pumping well was 1,000 gpm/ft, and the maximum water well level tidal range is about 2.52 ft, the well could theoretically pump about 2,500 gpm, and no drawdown would be observed if tides were rising at maximum. More commonly, observed water well levels could rise during pumping and fall during recovery, if tidal corrections are ignored. This oddity was actually seen during the pumping and recovery test.

Appendix C-1 shows ESTA calibration values for the 10-inch supply well near Kahuku. When ESTA was applied, rising-tide water well levels were overpredicted and falling-tide water well levels were underpredicted by 0.10 ft (4.5 percent error, 28 data sets) and 0.33 ft (33 percent error, 21 data sets), respectively. Error analysis reduced these errors to 0.06 ft (2.7 percent error) and 0.16 ft (16 percent error), respectively. This was obtained by decreasing ESTA-calculated, rising-tide water well levels by 1.91 percent, and increasing falling-tide water well levels by 5.95 percent.

Tidal response and arrival time calculations could not be made, because the Laie Bay high and low tidal peak data followed the observed well responses at Kahuku. Better corrections and analyses could be made if Kahuku tidal data were available.

The tidal corrected, Cooper-Jacob recovery of the observation well gave the best, though only fair, hydraulic analysis. The test included pumping the 10-inch supply well at 1,050 gpm for 8 hours, and recovering the very nearby 4-inch observation well for 3 hours. It indicated an aquifer transmissivity of about 2.92 mgd/ft (390,000 ft^2/day) and an hydraulic conductivity of about 36,500 gpd/ft^2 (4,900 ft/day). These values are on the order of magnitude estimated by Stephen L. Lau, Director of the University of Hawaii, Water Resources Research Center. They represent an increase in transmissivity of about 15-fold, and an increase in conductivity of more than 8-fold over the values of the Puerto Peñasco coquinoid aquifer.

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APPENDIX A-1

ESTA ALGORITHM

For Predicting Standing Water Levels

This algorithm computes standing water well levels in response to changes in sea levels due to tides. It requires initial sea and well calibration data, from which sea-well relationships are calculated. These relationships are assumed constant, or proportional to dimensionally identical new sea and well values. Tidal chart data are needed for the time period when projected standing water well levels are desired.

Plate 2 shows a sketch of key sea and well variables and relationships for falling tides.

Initial Sea Variables

These variables are used:

HTSS, high-tide sea stage, ft, above a datum such as mean low water
LTSS, low-tide sea stage, ft, above same datum
HTST, high-tide sea time, hrs
LTST, low-tide sea time, hrs

These sea variables are computed:

MSS, mean sea stage, ft, above same datum: MSS = (HTSS + LTSS) / 2
SSR, sea-stage range, ft: SSR = HTSS - LTSS
IHTST, HTST in minutes
ILTST, LTST in minutes
SSTI, sea-stage time interval, minutes: SSTI = / IHTST - ILTST /

Initial Well Variables

HTWS, high-tide well stage, ft, below a datum such as top of casing
LTWS, low-tide well stage, ft, below same datum
HTWT, high-tide well time, hrs
LTWT, low-tide well time, hrs

These well variables are computed:

MWS, mean well stage, ft, below same datum: MWS = (HTWS + LTWS) / 2
WSR, well-stage range, ft: WSR = / HTWS - LTWS /
IHTWT, HTWT in minutes
ILTWT, LTWT in minutes
WSTI, well-stage time interval, minutes: WSTI = / IHTWT - ILTWT /

Sea-Well Relationships

EDIF, differential between mean sea and well stages, ft: EDIF = (MSS - MWS)
TEFF, tidal efficiency, %: TEFF = (WSR x 100) / SSR
TTEFF, tidal time interval efficiency, %: TTEFF = (WSTI x 100) / SSTI
IHTRL, high-tide response lag, minutes: IHTRL = IHTWT - IHTST
ILTRL, low-tide response lag, minutes: ILTRL = ILTWT - ILTST
HEFF, high-tide response lag efficiency, %: HEFF = (IHTRL x 100) / WSTI
LEFF, low-tide response lag efficiency, %: LEFF = (ILTRL x 100) /WSTI

After sea-well relationships are calculated, the computer is ready to calculate projected water well levels from new tidal chart data and new water well level times. A set of tidal chart data, occurring before the projected water level time, is tried out.

New Sea Values

NHTSS, new high-tide sea stage, ft, same datum as initial sea variables
NLTSS, new low-tide sea stage, ft, same datum
NHTST, new high-tide sea time, hrs
NLTST, new low-tide sea time, hrs

These new sea values are computed:

NMSS, new mean sea stage, ft, same datum: NMSS = (NHTSS + NLTSS) / 2
NSSR, new sea-stage range, ft: NSSR = NHTSS - NLTSS
NIHTST, NHTST in minutes
NILTST, NLTST in minutes
NSSTI, new sea-stage time interval, minutes: NSSTI = / IHTST - ILTST /

New Well Values

NWST, new well-stage time, hrs -- given
NWL, new water-well level, ft, same datum as initial well variables -- unknown

This new well value is computed:

NIWST, NWST in minutes

From the sea-well relationships and new sea values, these new variable are calculated:

NMWS, new mean well stage, ft, same datum as initial well variables: NMWS = NMSS - EDIF
NWSR, new well-stage range, ft: NWSR = (TEFF x NSSR) / 100
NBASE, new base, ft: NBASE = NMWS - (NWSR / 2)
NWSTI, new well-stage time interval, minutes: NWSTI = (TTEFF x NSSTI) / 100

Falling Tide

If tide is falling, calculate:

NHTRL, new high-tide response lag, minutes: NHTRL = (HEFF x NWSTI) / 100
NIHTWT, new high-tide well time, minutes: NIHTWT = NIHTST + NHTRL
NILTWT, new low-tide well time, minutes: NILTWT = NIHTWT + NWSTI

If NIHTWT < NIWST $\leq$ NILTWT, then

$$NWL = NBASE + NWSR \sin\left[\left(\frac{NIWST - NILTWT}{NWSTI}\right) 90°\right]$$

If NIWST = NIHTWT, then NWL = NBASE.

If NILTWT < NIWST < NIHTWT, then a new set of sea values must be attempted until an appropriate set occurs.

Rising Tide

If tide is rising, calculate:

NLTRL, new low-tide response lag, minute: NLTRL = (LEFF x NWSTI) / 100
NILTWT, new low-tide well time, minutes: NILTWT = NILTST + NLTRL
NIHTWT, new high-tide well time, minutes: NIHTWT = NILTWT + NWSTI

If NILTWT < NIWST $\leq$ NIHTWT, then

$$NWL = NBASE + NWSR \cos\left[\left(\frac{NIWST - NILTWT}{NWSTI}\right) 90°\right]$$

If NIWST = NILTWT, NWL = NBASE + NWSR.

If NIHTWT < NIWST < NILTWT, then a new set of sea values must be attempted until an appropriate set occurs.

APPENDIX A-2

ESTA CALIBRATION VALUES

Puerto Peñasco, Sonora, Mexico

Test-Supply Well 2A
September 18, 1979
Falling Tide

HTSS = 13.3 ft
HTST = 0030 hrs
IHTST = 30 minutes

LTSS = 0.5 ft
LTST = 0630 hrs
ILTST = 390 minutes

MSS = 6.90 ft
SSR = 12.8 ft
SSTI = 360 minutes

HTWS = 29.64 ft
HTWT = 0320 hrs
IHTWT = 200 minutes

LTWS = 29.80 ft
LTWT = 1005 hrs
ILTWT = 605 minutes

MWS = 29.72 ft
WSR = 0.16 ft
WSTI = 405 minutes

EDIF = -22.82 ft
IHTRL = 170 minutes
TEFF = 1.25 %
HEFF = 41.98 %

ILTRL = 405 minutes
TTEFF = 112.50 %
LEFF = 100.00 %

Note: Datum for Test-Supply Well is top of casing, 0.77 ft above land surface, which is 32.09 ft above mean sea level. Datum for tides is mean sea level at Harbor in Puerto Peñasco.

APPENDIX A-3

ESTA ERROR ANALYSIS

Puerto Peñasco, Sonora, Mexico

Well No.	Tide	Average Overpredicted Water Level Percent	Feet	No. of Pts
TP1B	Rising	0.33	0.08	13
TS2A	Falling	0.04	0.01	9
TS3A	Rising	0.36	0.04	7
TS4A	Falling	0.13	0.04	8
TP5B	Rising	0.10	0.03	11
Average of 5 sites		0.19	0.04	
Average of sites 2 to 5		0.16	0.03	

APPENDIX B-1

TIDAL DERIVED TRANSMISSIVITIES

Puerto Peñasco, Sonora, Mexico

Test Site	Transmissivity, gpd/ft High Tide	Transmissivity, gpd/ft Low Tide	Distance of Test Site from Sea, ft	Tidal Efficiency, percent
1*	158,000	15,700	370	1.8
2**	940,000	167,000	910	1.2
3**	1,035,000	403,000	740	2.2
4**	630,000	367,000	690	2.7
5**	980,000	710,000	870	1.3

* Assumed Storativity, 0.004
**Assumed Storativity, 0.05

APPENDIX B-2

BOUNDARY AND TIDAL DERIVED TRANSMISSIVITIES
(Assumed storativity of 0.05)

Puerto Peñasco, Sonora, Mexico

Test Site	Transmissivity, gpd/ft High Tide	Transmissivity, gpd/ft Low Tide	Average
2	300,000	53,300	177,000
3	604,000	235,000	420,000
4	368,000	214,000	291,000
5	272,000	197,000	234,000

APPENDIX C-1

ESTA CALIBRATION VALUES

Kahuku, Oahu, Hawaii

Ten-Inch Supply Well
August 10, 1980
Rising Tide

LTSS = 0.2 ft
LTST = 0824 hrs
ILTST = 504 minutes

HTSS = 2.4 ft
HTST = 1535 hrs
IHTST = 935 minutes

MSS = 1.30 ft
SSR = 2.2 ft
SSTI = 431 minutes

LTWS = 6.60 ft
LTWT = 0820 hrs
ILTWT = 500 minutes

HTWS = 4.47 ft
HTWT = 1525 hrs
IHTWT = 925 minutes

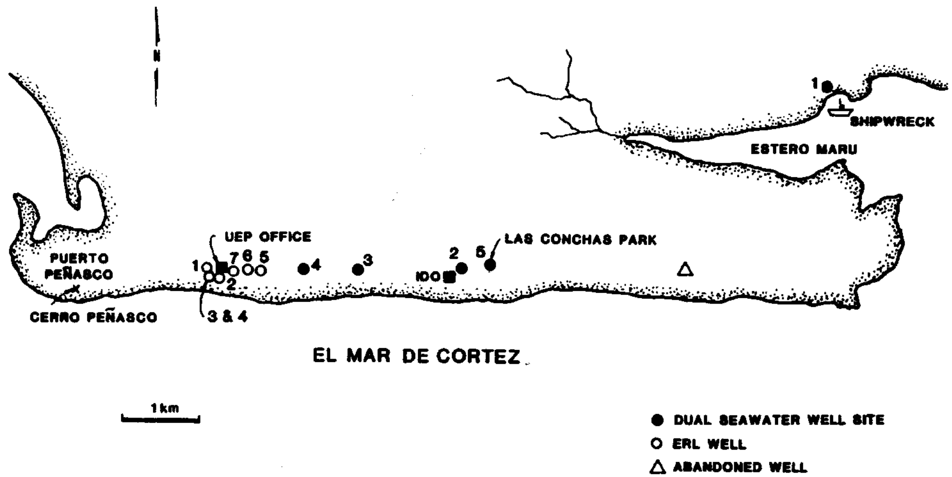
MWS = 5.54 ft
WSR = 2.13 ft
WSTI = 425 minutes

ILTRL = nil
LEFF = nil

IHTRL = nil
HEFF = nil

EDIF = -4.24 ft
TEFF = 96.8 %
TTEFF = nil

Note: Datum for Supply Well is top of casing, 0.40 ft above land surface. Land surface at well site is about 5 ft above sea level. Datum for tides is 0.8 ft below mean sea level, Laie Bay.



LOCATION OF TEST SITES
Puerto Peñasco, Sonora, Mexico

PLATE 1

PLATE 2

SEA AND WELL VARIABLES AND RELATIONSHIPS FOR A FALLING TIDE, ESTA ALGORITHM